

# CONSTRAINTS ON AXION-LIKE PARTICLES FROM $\gamma$ -RAY ASTRONOMY WITH H.E.S.S.

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## Abstract

Pseudoscalar particles like axion-like particles generically couple to two photons, giving rise to the possibility of oscillations with photons in an external magnetic field. These oscillations could lead to measurable imprints in the electromagnetic spectrum of astrophysical sources if the coupling to photons is strong enough. One possible signature is the presence of irregularities in a limited energy range of the spectrum. In this study, anomalous irregularities are searched for in the spectrum of the bright extragalactic TeV emitter PKS 2155-304 as measured by H.E.S.S. to put constraints on the coupling of light spin 0 particles to photons.

## 1 Introduction

Pseudoscalar particles are predicted in many extension of the Standard Model. A well-known example is the axion, which is the pseudo Nambu-Goldstone boson associated to the breaking of the U(1) symmetry introduced by Peccei and Quinn to solve the strong CP problem<sup>1</sup>. Strong constraints on the energy scale of the breaking of the symmetry are obtained by astrophysical observations<sup>2</sup>, implying that the mass of the axion should be lower than 1 eV. A generic property of pseudoscalar particles is their coupling to the electromagnetic field via a two-photon vertex. In the specific case of the axion, the coupling to photons is predicted to scale with its mass. However, more general low mass pseudoscalars with coupling and mass unrelated are expected from other exotic models<sup>3</sup>. Such particles are called axion-like particles (ALPs) and couple electromagnetically in the same way axions do.

The coupling of ALPs to two photons enables oscillations between photons and ALPs in an external magnetic field<sup>4</sup>. In  $\gamma$ -ray astronomy, these oscillations are sometimes considered as a possible mechanism responsible for the potential reduction of the opacity of the universe to TeV photons<sup>5</sup>. However, in ref. 6, a new signature of ALPs in the energy spectrum of bright  $\gamma$ -ray sources has been proposed. Because of the turbulent nature of the astrophysical magnetic fields crossed by the photon beam of a  $\gamma$ -ray emitter, the observed spectrum can be affected by strong irregularities in a limited energy range. These irregularities are expected around the critical energy  $E_c = m^2/(2g_{\gamma a}B)$  above which the strong mixing regime is attained, where  $m$  is the ALP mass,  $g_{\gamma a}$  the coupling constant and  $B$  the magnetic field strength. Fig. 1 shows an example of such irregularity pattern (upper panel), and the same pattern smeared by the energy resolution of approximately 15 % of H.E.S.S. (lower panel). Here, the initial photon beam is taken unpolarized and the survival photon probability cannot be lower than 1/2. The survival probability is computed using the matrix density formalism described in 7. For magnetic fields at the  $\mu$ G level typical of galaxy clusters and a coupling constant  $g_{\gamma a} = 10^{-10} \text{ GeV}^{-1}$  close to the upper limit set by the CAST experiment<sup>8</sup>,  $E_c$  is of order of 1 TeV for ALP masses of a few tens of neV. This means that the sensitivity of H.E.S.S. to ALPs lies in a limited range of mass between 10 neV and 100 neV. In the following, irregularities are searched for in the energy spectrum of the bright TeV blazar PKS 2155-304 measured by H.E.S.S.<sup>9</sup>.

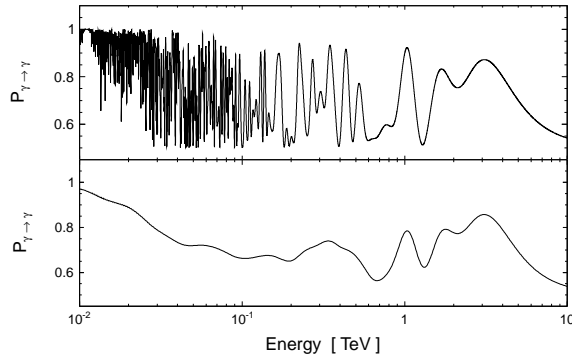


Figure 1: Transfer function for  $\gamma$ -rays mixing with ALPs in a galaxy cluster magnetic field (see text for details). Top panel : raw function. Bottom panel : Same function smeared with the energy resolution and bias of H.E.S.S.

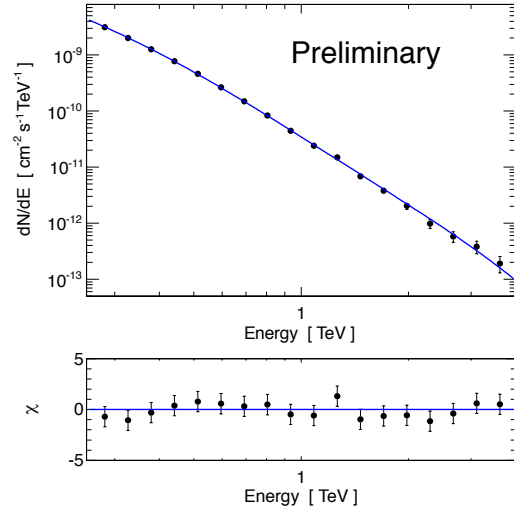


Figure 2: Time-averaged energy spectrum of PKS 2155-304 (black points) for the dataset used in the analysis. Top panel : the blue line is the best fit of a curved power-law with EBL absorption to the data. Bottom panel : relative residuals of the fit normalized to the errors.

## 2 Magnetic fields on the line of sight

PKS 2155-304 is a BL Lac object situated at redshift  $z = 0.116$  that is a powerful TeV emitter. This source is chosen here for two reasons. First, it has been extensively observed by H.E.S.S. and the high statistics available makes a precise determination of the spectrum possible<sup>10</sup>. Second, a small galaxy cluster of radius 372 kpc is observed around this source<sup>11</sup>, meaning that a magnetic field in the vicinity of the source is expected. The magnetic field in the galaxy cluster surrounding PKS 2155-304 is not measured. Usually, Faraday rotation measurements enable to probe the structure of the magnetic field in similar galaxy clusters, hosting FR I radio galaxies (believed to be the parent population of BL Lac objects)<sup>12</sup>. These studies report evidence for magnetic fields of the order of a few  $\mu\text{G}$  and turbulence in agreement with a Kolmogorov turbulence on scales as large as 10 kpc. In the following, a conservative value of 1  $\mu\text{G}$  is assumed for the magnetic field strength and a Kolmogorov power spectrum on scales between 1 and 10 kpc describes the turbulence.

Conversion of photons from PKS 2155-304 in the intergalactic magnetic field (IGMF) can also be considered. The IGMF is subject to large uncertainties and no measurement of its strength has been possible so far. The range of possible values is experimentally constrained between  $10^{-16}$  G and 1 nG. In the following, a value of 1 nG is assumed for the IGMF strength to derive the ALP exclusions. This means that they are deduced from the most optimistic model. The shape of the turbulence power spectrum is not clear too. A Kolmogorov power-law may not be relevant for the description of the IGMF turbulence. A single turbulent scale of 1 Mpc is assumed to simulate the conversion in the IGMF. Conversion inside the source itself, within the jet or radio lobes is not considered here because of the very uncertain nature of the magnetic fields.

### 3 H.E.S.S. Observations of PKS 2155-304

PKS 2155-304 has been observed by the H.E.S.S. phase I array of four imaging atmospheric Cherenkov telescopes that observe the  $\gamma$ -ray sky above a few hundreds of GeV<sup>13</sup>. Observations of PKS 2155-304 with H.E.S.S. during the flare of July 2006 are selected for the spectral analysis, for a total live-time of 13 hours. Data taken during the flare of July 2006 are selected in order to minimize possible bias in the spectrum reconstruction coming from mis-subtracted background that could mimic ALP patterns. During the high state, observations of the source are almost background free. The spectrum of the 45505  $\gamma$ -ray candidates is shown on Fig. 2. It is well-modeled by a curved power-law convolved by absorption on the EBL ( $dN/dE \propto (E/1\text{TeV})^{-\alpha-\beta \log(E/1\text{TeV})} e^{-\tau_{\gamma\gamma}(E)}$ ) with  $\alpha = 3.18 \pm 0.03_{\text{stat}} \pm 0.2_{\text{syst}}$ ,  $\beta = 0.32 \pm 0.02_{\text{stat}} \pm 0.05_{\text{syst}}$  and  $\tau_{\gamma\gamma}$  is the optical depth from the EBL model of Kneiske & Dole<sup>14</sup>. No significant irregularities appear in the spectrum so that it is used to constrain the coupling of ALPs to photons.

### 4 Method and results

A natural method to constrain the value of  $g_{\gamma a}$  would be to fit a spectral shape expected from  $\gamma$ -ALP oscillations on the spectrum measured by H.E.S.S. Here, the intrinsic spectrum of the source is not known, so that this method would have to rely on an assumption for the spectral shape that may be wrong. In this case, the limits deduced would be biased and could be optimistically too constraining. To bypass this issue, an estimator of the irregularities in the spectrum is used that does not make the assumption of a spectral shape. It is based on the assumption that the spectrum is log-linear on scale of three bins, which is justified in the context of the astrophysical processes involved. In each group of three consecutive bins, the level of irregularity is quantified by the deviation of the middle bin from the power-law defined by the side bins, taking all errors and correlations into account. The deviations are quadratically summed over all the groups of three consecutive bins to form the estimator  $\mathcal{I}$  of irregularities in the spectrum. The value of  $\mathcal{I}$  may depends on the binning of the spectrum. To estimate the uncertainty on  $\mathcal{I}$ , the binning is modified in size and position, which induce small variations of  $\mathcal{I}$  due to the reshuffling of some events. The average and root mean square of  $\mathcal{I}$  when varying the binning is  $\mathcal{I} = 4.10 \pm 0.65$ . The value of 4.75 is conservatively assumed in the following to obtain the constraints.

In order to estimate the level of irregularities induced by ALPs that can be accommodated by the H.E.S.S. spectrum, simulations of spectra that would be observed for various ALP parameters are performed. The exact turbulent configuration of the magnetic field is unknown so that the simulations are repeated for different realizations of the magnetic field. For one parameter set, the ensemble of all the  $\mathcal{I}$  measured on simulated spectra for different realizations of the magnetic field constitutes the PDF of  $\mathcal{I}$ . An example of such PDF is shown on Fig.3 for conversion in the galaxy cluster magnetic field and two values of the coupling strength,  $g_{\gamma a} = 0.5 \times 10^{-11} \text{GeV}^{-1}$  and  $g_{\gamma a} = \times 10^{-10} \text{GeV}^{-1}$ . If the measured value of  $\mathcal{I}$  is excluded by the PDF at a one-sided 95% probability, the parameters are excluded. In the case of Fig. 3, the second value for  $g_{\gamma a}$  is excluded while the first one is not.

The constraints obtained with this method for conversion in the galaxy cluster and in the IGMF are shown on Fig. 4. For the conversion in the galaxy cluster magnetic field, a conservative strength of 1  $\mu\text{G}$  is assumed so that the constraints derived are considered as safe and robust. Conversely, for the IGMF, an optimistic value of 1 nG is used and this limit is shown as an indication of the H.E.S.S. sensitivity with values usually assumed in the literature. The CAST limit is also shown on the plot. The H.E.S.S. exclusions improve the CAST limit in a restricted range of mass around a few tens of neV. H.E.S.S. is sensitive in a restricted mass range because the irregularities are expected in a limited energy range around the critical energy that defines

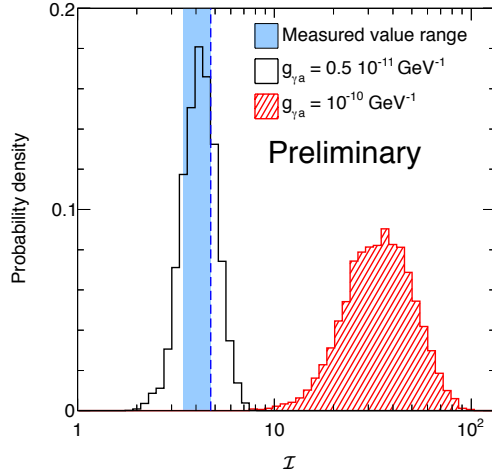


Figure 3: Predicted probability density functions of irregularity reconstructed with the fluctuation estimator for two ALP parameter sets. The vertical band correspond to measurements in the data with different bin sizes and the dashed line is the value used to set the limits.

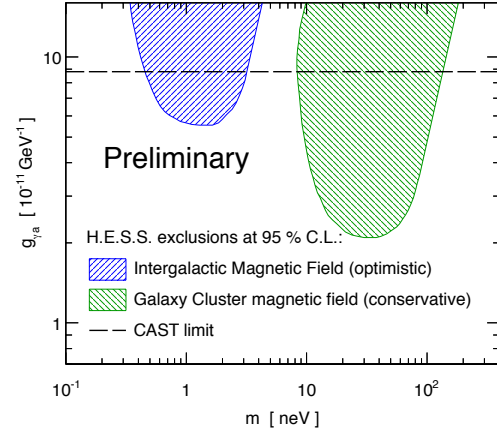


Figure 4: H.E.S.S. exclusion limits on the ALP parameters  $g_{\gamma a}$  and  $m$ . The blue dashed region on the left is obtained considering  $\gamma$ -ALP mixing in the IGMF with in an optimistic scenario with a 1 nG strength. The green dashed region on the right is obtained considering  $\gamma$ -ALP mixing in the galaxy cluster of PSK 2155-304.

the energy above which  $\gamma$ -ALP oscillations are possible. The range of energy that H.E.S.S. is sensitive to thus translates in a range of mass that can be probed. The limits that are shown on Fig. 4 are valid for any kind of scalar or pseudoscalar particles that couple to photons. The exclusion obtained with H.E.S.S. are the first exclusions on ALPs from  $\gamma$ -ray astronomy. In the future, observations including the fifth telescope of H.E.S.S. would lower the energy threshold of the spectral analysis and then enlarge the accessible mass range.

## Acknowledgments

See standard acknowledgements in H.E.S.S. papers not reproduced here due to lack of space. The support of the French PNHE (Programme National Hautes Energies) is also acknowledged.

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